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Title: Use of Ionizing Radiation to Improve Sensory and Microbial Quality of Fresh-Cut Green Onion Leaves

Author(s): X. Fan, B.A. Niemira, and K.J.B. Sokorai

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Use of Ionizing Radiation to Improve Sensory and Microbial Quality of Fresh-cut Green Onion Leaves

X. FAN, B.A. NIEMIRA, AND K.J.B. SOKORAI

ABSTRACT: Fresh-cut green onion leaves that received γ radiation doses of 0, 1, 2, and 3 kGy were stored at 3 °C for up to 14 d. Although 2 and 3 kGy of radiation completely eliminated microflora, the treatments frequently resulted in increased loss of aroma and deterioration of visual quality. In addition, radiation caused cellular membrane damage. Samples treated with 1 kGy of radiation had similar or better sensorial quality and a reduced microbial population than the controls throughout the 14 d of storage. Our results suggest that irradiation at a dose of 1 kGy can be used to enhance microbial safety of fresh-cut green onions without loss in quality attributes.

Keywords: food safety, γ irradiation, green onion, ionizing radiation, quality

Introduction

DUE TO ITS UNIQUE FLAVOR, GREEN ONION (*Allium fistulosum* L.) is widely used as seasoning in oriental and Mexican foods such as salads, dips, and soups.

Besides the uniqueness of flavor, onions, in general, also possess antibacterial and therapeutic properties (Augusti 1990). However, several recent outbreaks of foodborne illness have been associated with consumption of green onions contaminated with human pathogens. These pathogens include *Shigella* and hepatitis A (Cook and others 1995; CDC 1998; Dentinger and others 2001; CLADHS 2002). Parasites, such as *Cryptosporidium* species and *Cyclospora cayetanensis*, have also been reported in green onions and implicated in the outbreaks of foodborne illness (CDC 1998; Doller and others 2002). Furthermore, recent FDA produce surveys suggested high rates of *Shigella* in both domestically produced and imported green onions (FDA 2002a, 2002b). Another bacterium, *Campylobacter*, has been found in green onions sold at farmers' outdoor markets (Park and Sanders 1992). Pathogens may be present in water used for irrigation or in soil where the plant grows. Fresh and minimally processed (fresh-cut) vegetables can be contaminated during harvest, processing, and/or display (Beuchat 1996).

Green onions are harvested by uprooting of the whole plants (Hruschka 1974). Therefore, harvested green onions comprise roots, a compressed stem and leaves consisting of lower white sheathing leaf bases (pseudostem), and hollow upper green leaf blades (DeMason 1990). Two kinds of fresh-cut green onions are available for food service and chain restaurants. One is processed by trimming leaves, cutting roots, and removing all or part of the compressed stem (Park and others 1998; Hong and others 2000); the final products are long bundles of green onions consisting of leaf bases (stalks) and/or leaf blades. The other kind of fresh-cut green onion is much more highly processed by removing all roots, compressed stems, and most of the lower white leaf sheath, and cutting the green leaves (blades) transversely into small pieces. The final products mainly consist of green leaf rings. Some defects of this kind of fresh-cut green onion include opening of rings and a high percentage of sheathing leaf bases (white stalks). The processing used for this type of fresh-cut green onion severely damages plant tissues and provides nutrients and surfaces for pathogens to grow. In addition, the processing may cause pathogen cross-contamination of leaves from roots where human pathogens are often found.

Ionizing radiation is highly effective for inactivation of foodborne pathogens and parasites in various vegetables (King and Josephson 1982; Thayer and others 1996; Bidawid and others 2000). However, the effect of irradiation on sensory and microbiological quality of green onions is unknown. The objective of this study was to investigate the impact of ionizing radiation on sensory quality and microbiology of green onions.

Materials and Methods

Sample preparation

'Southport' green onions (*Allium fistulosum* L.) were purchased from a farm in Oxnard, Calif., U.S.A. through a local distributor 9 d after harvest. After storage at 3 °C overnight, the green leaf blades were trimmed and then sliced, using a sharp stainless-steel knife, into rings approximately 1 cm long. The onion pieces (rings) were then placed into a basket and submerged into 100 ppm NaClO solution (7 °C) for 1 min. During the treatment, the basket was shaken to provide uniformity of chlorine treatment. The samples were then drained and spin dried. The onion pieces were packaged in perforated zipper bags. Approximately 45 g of samples were in each bag for quality and sensory evaluation and 50 g of samples for microflora measurement. Each bag was regarded as a replicate. All preparation steps were conducted at 7 °C. After overnight storage at 3 °C, the fresh-cut green onions were γ irradiated to 0 (controls), 1, 2, and 3 kGy at 4 °C. After irradiation, samples were stored at 3 °C for up to 14 d. Quality attributes were assessed at 1, 5, 9, and 14 d. Microflora was measured at 1, 5, 8, and 14 d. There were 4 replicate bags for quality measurement and 3 separate bags for background microflora measurement. Separate bags were used for each storage period. There were a total of 112 bags.

Irradiation and dosimetry

The samples were irradiated using a self-contained cesium-137 γ radiation source (Lockheed Georgia Co., Marietta, Ga., U.S.A.) with a dose rate of 0.096 kGy/min. The dose rate was established using alanine transfer dosimeters from the Natl. Inst. of Standards and Technology (Gaithersburg, Md., U.S.A.). Corrections for source decay were made monthly. Variations in radiation dose absorption were minimized by placing the samples within a uniform area of the radiation field, by irradiating them within a polypropylene container (4-mm wall) to absorb Compton electrons, and by using the same geometry for sample irradiation during the entire study. Each replicate of bags was irradiated separately. During irradiation, temperature (4 °C) in the radiation chamber was controlled by flushing the chamber with cold nitrogen. To reduce possible effects of nitrogen during irradiation, all samples were placed in the chamber with nitrogen flushing for the same total period (32.88 min). Routine dosimetry was performed using 5-mm-dia alanine pellets (Bruker Instruments Inc., Billerica, Mass., U.S.A.). The pellets were placed into 1.2-mL cryogenic vials (Nalgene, Rochester, N.Y., U.S.A.), and the cryogenic vials were placed with the samples before irradiation. Absorbed doses were measured using a Bruker EMS 104 EPR analyzer and calculated in comparison with a standard curve. Actual doses were within 5% of the target doses.

Table 1 – Firmness (kg) of irradiated and nonirradiated fresh-cut green onions stored at 3 °C

Radiation dose	Storage time (d)							
(kGy)	1	5	9	14	$LSD_{0.05}$[a]	Linear	Quadratic	Cubic
0	24.3	24.9	25.1	20.1	4.3	NS[b]	NS	NS
1	25.4	26.4	24.0	24.5	6.2	NS	NS	NS
2	21.5	23.2	23.0	25.9	5.1	NS	NS	NS
3	21.1	22.8	21.2	21.0	4.9	NS	NS	NS
$LSD_{0.05}$[a]	3.6	5.6	5.8	5.4				
Linear	*	NS	NS	NS				
Quadratic	NS	NS	NS	*				
Cubic	NS	NS	NS	NS				

Fresh-cut green onions were exposed to 0, 1, 2, or 3 kGy of γ radiation at 4 °C and then stored at 3 /degree/C. Firmness was measured after 1, 5, 9, and 14 d of storage. The values are means of 4 replicates.
[a]The least significant difference at $P < 0.05$
NS or * indicates nonsignificant or significant at $P < 0.05$ level, respectively.

Color

A Hunter Miniscan XE colorimeter with a 26-mm measuring aperture (Hunter Associates Laboratory, Reston, Va., U.S.A.) was used to assess green onion color. D65/10° was the illuminant/viewing geometry. After calibration with the standard white and black plates, 10-g samples were placed into a measuring cup (Hunter Associates Laboratory), and readings were made through the cup. Two readings were made per bag, and there were 8 readings per treatment. Chroma and hue values were calculated from a and b values. (McGuire 1992). Hue values represent the true color of samples, and chroma is an index of color saturation.

Texture

Texture was determined using the TA.XT2i Texture Analyzer and a mini-Kramer shear press with 5 blades (Texture Technology Corp, Scarsdale, N.Y., U.S.A.). A 5-g sample was placed into the press holder, and then the 5-blade plunger moved down at 2 mm/s to 1 cm below the bottom of the holder. Maximum force was recorded using the Texture Expert software (version 1.22, Texture Technology Corp, Scarsdale, N.Y., U.S.A). There were a total of 8 measurements for each treatment (2 readings each bag).

Sensory evaluation

Each sample was visually rated by 3 judges according to systems developed by Loaiza and Cantwell (1997) and Cantwell and others (2001). Overall quality was scaled on a 9 to 1 scale, where 9 = excellent, 7 = good, 5 = fair, 3 = poor, and 1 = unusable. A score of 6 was regarded as the limit of marketability. Greenness was rated on a 5 to 1 scale, where 5 = dark green, fresh harvested, 4 = bright green, 3 = light green with yellowing or browning affecting 5% or less of leaves, 2 = light green with noticeable yellowing or browning on 5% to 20% of leaves, and 1 = light green with > 20% of yellowing or browning. Typical aroma was scored on a 5 (maximum) to 1 (none) scale. Decay was evaluated by weighing decayed leaves and was expressed as percent decay. Leaves that had brown or black discoloration were regarded as decayed.

Electrolyte leakage

Electrolyte leakage measures integrity of plant cells and tissues. An increase in electrolyte leakage indicates deterioration in cellular membrane systems. To measure electrolyte leakage, 5 g of green onion pieces were placed into 100-mL bottles containing 50 mL of deionized water and incubated for 60 min at 23 °C with gentle shaking. Electrical conductivity of the water was then measured using a CON 100 conductivity meter (Oakton, Singapore). The samples in the bottles were then autoclaved for 25 min, and a final conductivity reading was taken for total electrolytes. Electrolyte leakage was expressed as a percentage of the total electrolyte readings.

Measurement of carotenoid and chlorophyll

Samples (5 g) were homogenized on ice with 20-mL cold acetone using a homogenizer (Virtis, Gardiner, N.Y., U.S.A.) at a speed setting of 70 for 2 min. The homogenate was filtered through glass fiber filters (GF/D, Whatman, Maidstone, Kent, UK) under vacuum, and pigments in the residue (the filter cake layer) was extracted with another 20 mL acetone and filtered again. The combined filtrate was transferred to a 50-mL volumetric flask and adjusted to 50 mL with acetone. Acetone extract (2 mL) was added to a 10-mL centrifuge tube followed by 1 mL deionized water and 3 mL diethyl ether. The tube was sealed with a cap and shaken. Absorbances at 661.6 nm, 643.2 nm, and 470 nm in the diethyl ether phase were measured using a Shimadzu UV-1601 spectrophotometer (Shimadzu Scientific Instruments, Columbia, Md., U.S.A.). The contents of chlorophyll *a*, chlorophyll *b*, and carotenoid were calculated using equations developed by Lichtenthaler (1987). Total chlorophyll was the sum of chlorophyll *a* and *b*.

Microflora

Micorflora was measured at 0, 1, 5, 8, and 14 d of storage. Each sample consisted of a stomacher bag containing 50 g of irradiated green onions. To each sample bag, 200 mL sterile Butterfield's phosphate buffer (BPB) (Applied Research Institute, Newtown, Conn., U.S.A.) was added. The bag was closed and agitated (60 s) to obtain a surface wash of the sample. A 1-mL aliquot was serially diluted in BPB in 1:10 increments to 10^5. Dilutions were pour-plated with tryptic soy agar (TSA), 3 plates per dilution. Plates were inverted and incubated at 37 °C overnight. Plates were counted with an automated plate counter. The experiment was performed 3 times in replications run concurrently. The data from the 3 replications were pooled (n = 9).

Statistical analysis

There were 4 replicate packages for quality measurement and 3 replicate packages for microflora assay. Each package of samples was regarded as a replicate. Data were subjected to statistical analysis using SAS ver. 6.12 (SAS Inst., Raleigh, N.C., U.S.A.). Various quality parameters as functions of radiation dose were analyzed by the least significant difference (LSD) analysis using the general linear model (GLM) procedure. The linearity effect of radiation dose was analyzed using orthogonal comparisons, and significance of polynomials was calculated using the Contrast statement of the GLM procedure.

Results and Discussion

COMPARED WITH THE NONIRRADIATED controls, firmness of fresh-cut green onions irradiated at all doses was similar to the controls at either 1, 5, or 9 d of storage (Table 1). After 14 d of storage, green onions irradiated at 2 kGy had higher firmness than the controls, whereas samples irradiated at other doses had similar firmness as the controls. During the 14 d of storage at 3 °C, firmness of all samples did not change significantly. In general, irradiation at doses up to 3 kGy did not consistently affect firmness.

Compared with the nonirradiated controls, samples irradiated at 2 and 3 kGy had lower chroma and higher hue values than controls at day 9 (Table 2). The higher hue values observed in 2- and 3-kGy irradiated green onions indicate that these samples were slightly greener than controls. Chroma is an index of color saturation. The lower chroma values of 2- and 3-kGy irradiated samples indicate the color of samples was less saturated or duller than the controls. Samples that received 1 kGy of radiation had similar instrumental color values as the controls during the entire storage period. During the 14 d of storage, chroma values of nonirradiated samples and of those exposed to 2 and 3 kGy of radiation increased while hue values of these samples decreased, judged from the orthogonal analysis. On the contrary, chroma and hue values of 1-kGy irradiated samples did not change during storage. There was no significant ($P < 0.05$) difference in L values (lightness) among the samples (data not shown).

There was no difference in total chlorophyll content or carotenoid content at day 1 (Table 3). At day 5, total chlorophyll content and carotenoid content increased linearly with higher radiation dose. Samples treated with 3 kGy of radiation had higher chlorophyll and carotenoid content than the controls. The increased carotenoid content by irradiation was also observed at day 9. However, after 14 d of storage, all samples became similar in chlorophyll or carotenoid content. Chlorophyll *a* contributed to most of the total chlorophyll content. The chlorophyll *a*/*b* ratios of all samples were generally in the range of 2.5:1 at day 1; however, the ratios decreased linearly during storage.

Instrument-based color measurement of leaves yielded somewhat different results than direct chemical analysis of pigment content. Color measurement indicated that 2- and 3-kGy irradiated samples appeared greener than the controls at day 9, whereas total chlorophyll content of the samples was higher than controls at day 5. The most probable explanation is that differences in the content of carotenoid (yellow pigment) among the samples combined with chlorophyll contribute to the overall instrument-based color values.

Earlier studies suggest that high doses of radiation reduced chlorophyll and carotenoid content of frozen vegetables (Franceschini and others 1959; Wishnetsky and others 1959). Our results suggest that fresh-cut green onions irradiated at doses up to 3 kGy had similar or higher chlorophyll and caro-

Table 2—Chroma and hue values of irradiated and nonirradiated fresh-cut green onions stored at 3 °C

Dose	Storage time (d)							
(kGy)	1	5	9	14	$LSD_{0.05}$[a]	Linear	Quadratic	Cubic
Chroma								
0	24.8	26.9	28.7	28.7	2.5	**	NS	NS
1	26.7	25.1	26.7	26.5	3.5	NS		
2	23.3	25.9	25.3	27.8	2.0	***	NS	NS
3	25.2	26.8	25.6	29.0	2.4	**	NS	NS
$LSD_{0.05}$[a]	2.8	2.5	2.3	3.0				
Linear	NS[b]	NS	**	NS				
Quadratic	NS	NS	NS	NS				
Cubic	*	NS	NS	NS				
Hue								
0	111.4	110.3	108.7	107.1	1.6	***	NS	NS
1	110.9	110.1	110.4	109.5	1.9	NS	NS	NS
2	112.8	111.1	110.9	108.6	1.3	***	NS	NS
3	111.7	110.5	111.0	108.7	1.5	***	NS	NS
$LSD_{0.05}$[a]	1.6	1.4	1.4	1.9				
Linear	NS	NS	**	NS				
Quadratic	NS	NS	NS	*				
Cubic	*	NS	NS	NS				

Samples were exposed to 0, 1, 2, or 3 kGy of g radiation at 4 °C and then stored at 3 °C. Color was measured using a colorimeter after 1, 5, 9, and 14 d of storage. The values are means of 4 replicates.
Storage time (d)
[a]The least significant difference at $P < 0.05$.
NS, *, **, or *** indicates nonsignificant or significant at $P < 0.05$, 0.01, and 0.001 levels, respectively.

Table 3—Pigments of irradiated and nonirradiated fresh-cut green onions stored at 3 °C

Dose	Storage time (d)							
(kGy)	1	5	9	14	$LSD_{0.05}$[a]	Linear	Quadratic	Cubic
Total chlorophyll								
0	13.51	12.42	10.54	13.81	3.18	NS	*	NS
1	14.65	14.41	11.22	13.46	1.71	*	*	**
2	15.80	14.00	11.31	12.73	2.49	**	*	NS
3	14.90	15.07	11.94	14.31	2.11	NS	NS	*
$LSD_{0.05}$[a]	2.90	1.65	1.39	3.27				
Linear	NS	**	NS	NS				
Quadratic	NS	NS	NS	NS				
Cubic	NS	NS	NS	NS				
Chlorophyll *a*/chlorophyll *b*								
0	2.55	2.46	2.39	2.45	0.07	***	**	NS
1	2.56	2.37	2.48	2.33	0.13	**	NS	*
2	2.48	2.34	2.41	2.21	0.11	***	NS	*
3	2.52	2.45	2.47	2.19	0.06	***	***	**
$LSD_{0.05}$[a]	0.09	0.08	0.12	0.10				
Linear	NS	NS	NS	***				
Quadratic	NS	**	NS	NS				
Cubic	NS	NS	NS	NS				
Carotenoid								
0	3.26	3.11	2.56	3.56	0.80	NS	*	NS
1	3.60	3.56	2.82	3.49	0.45	NS	*	**
2	3.84	3.46	2.81	3.22	0.61	*	*	NS
3	3.68	3.74	2.95	3.57	0.50	NS	NS	*
$LSD_{0.05}$[a]	0.68	0.41	0.32	0.84				
Linear	NS	*	*	NS				
Quadratic	NS	NS	NS	NS				
Cubic	NS	NS	NS	NS				

Samples were exposed to 0, 1, 2, or 3 kGy of γ radiation at 4 °C and then stored at 3 °C. Chlorophyll and carotenoids were measured after 1, 5, 9, and 14 d of storage. The values are means of 4 replicates.
[a]The least significant difference at $P < 0.05$.
[b]NS, *, **, or *** indicates nonsignificant or significant at $P < 0.05$, 0.01, and 0.001 levels, respectively.

Table 4—Visual quality of irradiated and nonirradiated fresh-cut green onions stored at 3 °C

Dose (kGy)	Storage time (d) 1	5	9	14	$LSD_{0.05}$[a]	Linear	Quadratic	Cubic
Overall (9-1)								
0	8.5	8.0	7.2	5.2	0.4	***[b]	***	NS
1	8.5	8.0	7.4	5.4	0.6	***	**	NS
2	8.5	7.5	7.0	5.3	0.7	***	NS	NS
3	8.5	7.3	7.1	4.8	0.6	***	*	*
$LSD_{0.05}$[a]		0.3	0.6	0.9				
Linear		***[b]	NS	NS				
Quadratic		NS	NS	NS				
Cubic		NS	NS	NS				
Greenness (5-1)								
0	4.8	4.5	3.8	3.9	0.3	***	**	**
1	4.8	4.5	3.8	4.0	0.3	***	**	**
2	4.8	4.5	3.6	4.0	0.3	***	***	***
3	4.8	4.2	3.6	3.7	0.3	***	***	NS
$LSD_{0.05}$[a]	0.2	0.3	0.3	0.2				
Linear	NS	NS	NS	*				
Quadratic	NS	NS	NS	*				
Cubic	NS	NS	NS	NS				
Aroma (5-1)								
0	4.7	4.1	3.1	3.8	0.5	***	***	**
1	4.5	4.3	3.3	3.6	0.4	***	*	**
2	4.4	3.6	3.1	2.8	0.4	***	*	NS
3	4.0	3.3	3.1	2.7	0.3	***	NS	NS
$LSD_{0.05}$[a]	0.4	0.5	0.4	0.4				
Linear	***	***	NS	***				
Quadratic	NS	NS	NS	NS				
Cubic	NS	NS	NS	NS				

Samples were exposed to 0, 1, 2, or 3 kGy of γ radiation at 4 °C and then stored at 3 °C. Visual quality was assessed using a colorimeter after 1, 5, 9, and 14 d of storage. The values are means of 4 replicates.
[a]The least significant difference at $P < 0.05$.
[b]NS, *, **, or *** indicates nonsignificant or significant at $P < 0.05$, 0.01, and 0.001 levels, respectively.

tenoid content than controls. The results presented herein are very similar to our earlier findings on alfalfa sprouts (Fan and Thayer 2001). Chlorophyll and carotenoid content of alfalfa sprouts was slightly promoted by irradiation at 7 d of storage at 7 °C, and sprouts irradiated at 2.6 kGy had lower ratio of chlorophyll *a* to *b* compared with the nonirradiated ones. Free radicals generated during irradiation may act as stress signals and may trigger some stress responses, resulting in higher chlorophyll and carotenoid content.

Overall visual quality deteriorated during storage for all samples (Table 4). After 14 d of storage, the quality of all samples became unmarketable. It appears that maximum shelf life for the green onions was about 9 d. Irradiation did not affect overall quality except at d 9, when the quality of 2- and 3-kGy irradiated samples was inferior to 0- and 1-kGy irradiated samples, probably due to a slightly higher decay rate and a watery appearance observed on the samples.

All samples had similar greenness scores throughout the period of investigation except the 3-kGy irradiated samples, which had lower greenness scores than the controls at d 14 (Table 4).

Typical aroma of samples decreased linearly with higher radiation dose and longer storage time (Table 4). Samples treated with 2 and 3 kGy of radiation had lower aroma scores than the controls at d 1, 5, and 14. However, 1-kGy irradiated samples always had similar aroma scores compared with controls during the entire investigation period. It appears that irradiation may affect the generation of volatile compounds responsible for the pungent odor. Compounds responsible for the aroma of green onions are mainly sulfur-containing compounds (Boelens and others 1971). An important area of future research will be to determine more specifically what compounds are reduced by irradiation.

The incidence of decay was higher in 3-kGy irradiated samples than in 1-kGy irradiated samples at day 5, and 1- and 2-kGy irradiated samples had decay rates similar to those of the controls (Table 5). However, after 9 d of storage, samples treated with 1 kGy of radiation had significantly ($P < 0.05$) lower decay than the controls. After 14 d of storage, both 1- and 2-kGy irradiated samples had lower decay than the controls. Decay may be caused by both senescence and irradiation damage.

Irradiation linearly increased electrolyte leakage of green onions measured at days 1 and 5 (Table 6). After 9 d storage, 1-kGy irradiated samples had lower electrolyte leakage than the controls, whereas 2- and 3-kGy irradiated samples had electrolyte leakage similar to the controls. After 14 d of storage, samples irradiated at 2 and 3 kGy had lower leakage than the controls. Electrolyte leakage of control samples increased linearly during storage, whereas leakage from samples irradiated at 1 and 2 kGy did not have significant change during storage. These results indicate that irradiation as well as the age of tissues may influence cellular membrane and consequently electrolyte leakage of green onions.

The membrane system of plant tissues is the boundary of all living cells and plays an important role in maintaining the homeostasis and normal physiological processes. Many enzymes and proteins also are embedded on membranes. Therefore, changes in the membrane will lead to the alteration and loss of normal physiological processes, and even to the death of plant tissues. The loss of cytoplasm from the cell through the damaged membranes is known as electrolyte leakage. Electrolyte leakage has been used as an index of cellular membrane integrity (Inaba and Crandall 1988; Whitlow and others 1992). Membrane deterioration is a general feature of natural senescence (Mitsuhashi and others 1998; Voisine and others 1991). Our results suggested that electrolyte leakage of control green onions increased during storage, particularly from d 9 to d 14, suggesting senescence and membrane deterioration of the tissues occurred in the period. These results are generally in agreement with our quality observation on control samples, which deteriorated rapidly from d 9 to d 14 as indicated by overall visual quality and decay. Ionizing radiation influences physiological process through the involvement of free radicals generated from radiolysis of water. The membrane is one of the targets of free radicals. Enhanced rates of ion leakage by γ radiation have been reported in several plant tissues (Lester and Wolfenbarger 1990; Hayashi and others 1992). Our results show that irradiation increased electrolyte leakage at days 1 and 5. However, irradiation is also known to delay ripening and senescence of certain fruits and vegetables (Dong and others 1994; Lester and Whitaker 1996). In this study, the level for electrolyte leakage increased during storage for nonirradiated samples, but remained essentially stable for samples irradiated at 1 and 2 kGy.

The initial total aerobic plate count (TAPC) of control samples was 4.6 colony-forming units (CFU)/g tissues (Figure 1). Immediately after irradiation, a dose of 1 kGy reduced TAPC to a level below the limit (2.1

CFU/g) of detection, resulting in a more than 2.5 log reduction. During storage, TAPC increased on both nonirradiated control and 1-kGy irradiated samples. The difference in TAPC between the 1-kGy irradiated samples and the control became smaller during storage. At d 14, the difference in TAPC was about 0.8 log between the 2 samples. TAPC of 2- and 3-kGy irradiated samples was below detection limit throughout the entire investigation period. The results were similar to our earlier observation on cilantro leaves (Fan and others 2002).

Farkas and others (1997) showed that ionizing radiation at 1 kGy reduced loads of bacteria, improved microbiological shelf life, and extended sensory quality of precut peppers and carrots. Prakash and others (2000a) found that a dose of 0.35 kGy of γ radiation decreased aerobic counts by 1.5 logs on cut romaine lettuce, and the difference was maintained for the 22-d storage at 4 °C. A 10% loss in firmness was, however, observed by the radiation dose. Prakash and others (2000b) also found that 1.0 kGy of radiation eliminated *Listeria monocytogenes* and *Escherichia coli* inoculated on diced celery while extending shelf life by 1 wk. A study of fresh-cut iceberg lettuce suggests that lettuce can tolerate up to 1 kGy of radiation without loss in quality attributes (Fan and Sokorai 2002). Doses higher than 1 kGy resulted in deteriorated quality. It appears that fresh-cut green onions have similar tolerance to radiation compared with lettuce.

Park and others (1998), working on 5- and 10-cm-long leaf bases of green onions, found that microbial quality deteriorated with severity of cutting. They also suggested that removal of the root, a potential source for microbial contamination, reduced microbial load in garlic. Cantwell and others (2001) studied the effect of heat treatment on quality and microbial population of minimally processed green onions (leaf blades and stalks). They found the heat treatment (52.5 °C) resulted in higher respiration rate, but did not affect overall visual quality. They concluded that treatment with 52.5 °C water alone or in combination with chlorine was more effective than use of water or chlorine solutions for initial microbial disinfection. Irradiation can be combined with warm water treatment and modified atmosphere packaging to improve quality (Fan and others 2003).

Overall visual quality suggested all samples were below the limit of marketability at d 14. Storage time of 14 d was therefore too long for preservation of fresh-cut green onions in the absence of any other control measures. Controlled atmosphere packaging, heat treatment, or other intervention technologies may be combined with irradiation to increase shelf life and safety of fresh-cut green onions.

The most important quality attributes to herbs are visual quality and aroma (Cantwell and Reid 1993). Our results indicate that visual quality of fresh-cut green onions was not consistently affected by irradiation. However, samples exposed to irradiation, particularly at 2 and 3 kGy, developed a watery appearance (data not shown). The watery and soaked appearance (sogginess) also was observed in fresh-cut lettuce (Fan and Sokorai 2002). The watery appearance may be related to irradiation-induced cellular leakage, flaccidity, and loss of tissue integrity. Irradiation also tended to decrease the typical aroma of green onions. The decrease in aroma could be a factor for the application of irradiation on fresh-cut green onions.

Table 5—Decay (%) of irradiated and nonirradiated fresh-cut green onions stored at 3 °C

Radiation dose	Storage time (d)							
(kGy)	1	5	9	14	$LSD_{0.05}$[a]	Linear	Quadratic	Cubic
0	0	2.9	12.7	22.9	2.8	***[b]	*	*
1	0	2.5	8.3	10.8	4.8	***	NS	NS
2	0	4.3	10.2	12.2	3.8	***	NS	NS
3	0	5.9	14.3	17.1	3.9	***	NS	NS
$LSD_{0.05}$[a]		3.1	3.9	6.0				
Linear		*[b]	NS	NS				
Quadratic		NS	**	**				
Cubic		NS	NS	NS				

Samples were exposed to 0, 1, 2, or 3 kGy of γ radiation at 4 °C and then stored at 3 °C. Decay was assessed after 1, 5, 9, and 14 d of storage. The values are means of 4 replicates.
[a]The least significant difference at $P < 0.05$.
[b]NS, *, **, or *** indicates nonsignificant or significant at $P < 0.05$, 0.01, and 0.001 levels, respectively.

Table 6—Electrolyte leakage (%) of irradiated and nonirradiated fresh-cut green onions stored at 3 °C

Radiation dose	Storage time (d)							
(kGy)	1	5	9	14	$LSD_{0.05}$[a]	Linear	Quadratic	Cubic
0	13.3	11.2	23.3	39.2	7.4	***	**	NS
1	20.6	14.8	17.1	26.4	13.7	NS	NS	NS
2	18.8	16.8	21.1	19.9	3.5	NS	NS	*
3	21.4	22.1	25.2	24.9	3.4	*	NS	NS
$LSD_{0.05}$[a]	3.9	2.3	6.5	14.2				
Linear	**	***	NS	*				
Quadratic	NS	NS	NS	NS				
Cubic	*	NS	NS	NS				

Samples were exposed to 0, 1, 2, or 3 kGy of γ radiation at 4 °C and then stored at 3 °C. Electrolyte leakage was measured after 1, 5, 9, and 14 d of storage. The values are means of 4 replicates.
[a]The least significant difference at $P < 0.05$.
NS, *, **, or *** indicates nonsignificant or significant at $P < 0.01$, 0.05, and 0.001 levels, respectively.

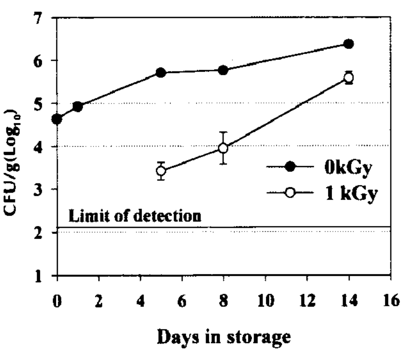

Figure 1—Total aerobic plate count (TAPC) of fresh-cut green onions during storage at 3 °C. Green onion samples were irradiated with 0, 1, 2, or 3 kGy of γ radiation at 4 °C and then stored at 3 °C. All data points represent means from 3 analyses accompanied by standard error bars. Standard error is smaller than the size of the symbol when the error bar is absent. Samples that received 2 and 3 kGy of radiation had TAPC below the detection limit.

Conclusions

OUR RESULTS SUGGEST THAT IRRADIATION at doses up to 3 kGy did not consistently affect firmness, overall visual quality, color or chlorophyll, and carotenoid content. However, 3-kGy irradiated samples had a higher decay rate and 2-kGy irradiated samples often had lower scores of aroma compared with 1-kGy irradiated samples or controls. Samples treated with 1 kGy of radiation had similar or better quality than controls and yet reduced microbial population throughout the storage period. Ionizing radiation at a dose of 1 kGy can be used to reduce microbial population of fresh-cut green onions without any deteriorated effect on product quality.

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Authors Fan, Niemira, and Sokorai are with the U.S. Dept. of Agriculture, Agricultural Research Service, Eastern Regional Research Center, Wyndmoor, PA 19038. Direct inquiries to author Fan (E-mail xfan@errc.ars.usda.gov).